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# The CALorimetric Electron Telescope (CALET) for high-energy astroparticle physics on the International Space Station

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**Abstract.** The CALorimetric Electron Telescope (CALET) is a space experiment, currently under development by Japan in collaboration with Italy and the United States, which will measure the flux of cosmic-ray electrons (and positrons) up to 20 TeV energy, of gamma rays up to 10 TeV, of nuclei with Z from 1 to 40 up to 1 PeV energy, and will detect gamma-ray bursts in the 7 keV to 20 MeV energy range during a 5 year mission. These measurements are essential to investigate possible nearby astrophysical sources of high energy electrons, study the details of galactic particle propagation and search for dark matter signatures. The main detector of CALET, the Calorimeter, consists of a module to identify the particle charge, followed by a thin imaging calorimeter (3 radiation lengths) with tungsten plates interleaving scintillating fibre planes, and a thick energy measuring calorimeter (27 radiation lengths) composed of lead tungstate logs. The Calorimeter has the depth, imaging capabilities and energy resolution necessary for excellent separation between hadrons, electrons and gamma rays. The instrument is currently being prepared for launch (expected in 2015) to the International Space Station ISS, for installation on the Japanese Experiment Module - Exposure Facility (JEM-EF).

## 1. Introduction

The CALorimetric Electron Telescope CALET [1] [2] will be installed on the International Space Station (ISS) in 2015, with the aim of performing accurate and long-duration observations of high-energy cosmic radiation, including charged particles and photons.

An overview of the CALET mission and apparatus is given in Sect. 2, while Sect. 3 contains a selection of major science items which will be addressed by CALET.

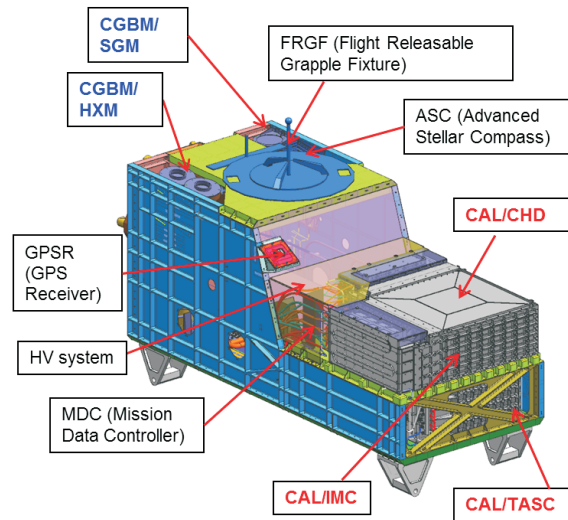
## 2. Overview of CALET experiment

The CALET apparatus is currently in advanced integration and test phase and scheduled to be launched in space in 2015 with the Japanese rocket HTV-5, for installation on the Japanese Experiment Module - Exposure Facility (JEM-EF) on the ISS and subsequent operation for a target duration of 5 years.

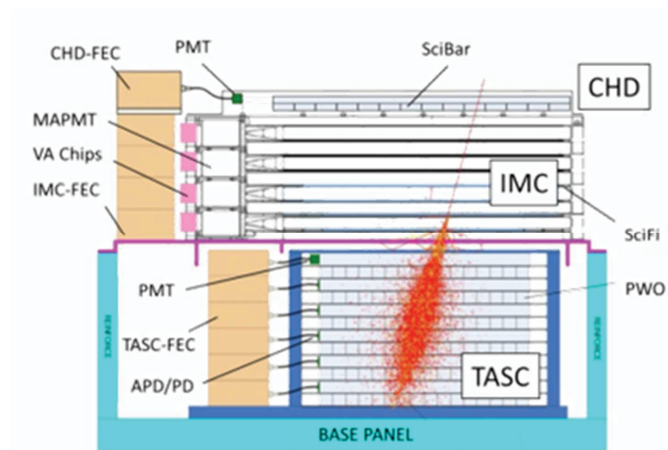
The CALET payload (see figure 1) includes scientific and auxiliary equipment for a total mass of 650 kg, dimensions of  $1.9 \times 0.8 \times 1.0$  m<sup>3</sup>, nominal power consumption of 650 W. The main scientific instruments are the electromagnetic calorimeter (CALET-CAL, see Sect. 2.1) and the gamma-ray burst monitor (CGBM, see Sect. 2.2).

### 2.1. CALET-CAL instrument

The CALET calorimeter (see figure 2) is composed of a charge detector (CHD), a pre-shower imaging calorimeter (IMC) and a total absorption calorimeter (TASC). It is optimized for



**Figure 1.** Drawing of the CALET payload. On the ISS the payload will be installed in such a way to have open sky on top, Earth on bottom.



**Figure 2.** Drawing of the CALET-CAL instrument, with a typical shower of secondary particles generated by a 1 TeV electron incident from top.

particle identification and energy measurement of several cosmic-ray species:

- electrons and positrons in the 1 GeV - 20 TeV energy range (with no charge sign discrimination);
- photons from few GeV to  $\sim 10$  TeV;
- nuclei up to the Fe region, with energy from tens of GeV to  $\sim 1$  PeV;
- ultra-heavy ( $Z > 28$ ) nuclei with  $E > 600$  MeV/nucleon (in this case, with no energy measurement).

The CHD, positioned on top of the IMC structure, is composed of two layers of plastic scintillator with mutually orthogonal segmentation in 14 bars (SciBars), each of dimensions  $3.2 \times 1.0 \times 44.8$  cm<sup>3</sup> and read by a photo-multiplier tube (PMT, Hamamatsu Photonics R7400U-06) and front-end circuit (FEC) with charge sensitive amplifier, for a total of 28 channels. The

CHD determines the charge absolute value  $|Z|$  of the incoming charged particle, through the  $Z^2$  dependence of the specific ionization loss. The very low uncertainty in the  $Z$  measurement (0.1 for light nuclei up to B, 0.3 in the Fe region) allows for resolving individual chemical elements with  $Z$  from 1 to 40 [3].

The IMC is a finely segmented sampling calorimeter, with surface area of  $45 \times 45 \text{ cm}^2$  and total thickness of 3 radiation lengths  $X_0$ ; internally, 8 double layers of scintillating fibres (SciFi,  $1 \text{ mm}^2$  cross-section) are interleaved with a sequence of 7 tungsten plates: 5 of thickness  $0.2 X_0$  and 2 of thickness  $1.0 X_0$ . The fibres of each double layer are mutually orthogonal and arranged in belts, each read by a 64-channel multi-anode PMT (MAPMT, Hamamatsu Photonics R7600-M64) and VA front-end ASIC circuit, for a total of 7168 channels. The IMC fine granularity allows for precise determination of the incoming particle trajectory, localization of the starting point of the secondary shower possibly generated, discrimination of the primary incident particle against possible backscattering from the shower developing in the IMC and underlying TASC.

The TASC is a homogeneous calorimeter made of 192 lead tungstate (PWO) logs with dimensions  $20 \times 19 \times 320 \text{ mm}^3$  and arranged in 12 layers, oriented along alternatively orthogonal directions. Each log in the top layer is read by a PMT for use in the trigger system, together with CHD and IMC signals. A dual photodiode / avalanche photodiode system (APD/PD, Hamamatsu Photonics S8664-1010/S1227-33BR) is used for read-out of the other layers. The TASC is specifically designed to measure the energy of the incident particle with excellent resolution: 2% (3%) for electrons (gamma-rays) with energy  $E > 10 \text{ GeV}$ , better than 35% for nuclei up to  $\sim 100 \text{ TeV}$  energy.

Moreover (see e.g. [4]), by exploiting the TASC and IMC shower imaging capabilities, a proton rejection power of  $\sim 1 \cdot 10^5$  can be achieved in the electron sample, with a selection efficiency better than 80%, sufficient to keep the proton contamination below a few percent in the observation of cosmic-ray electrons in the multi-TeV region.

The total thickness of the CALET-CAL instrument is equivalent to  $30 X_0$  and 1.5 nuclear interaction lengths  $\lambda_I$ . Its effective geometrical factor is  $\sim 0.12 \text{ m}^2\text{sr}$  for high-energy electrons and nuclei. The angular resolution is better than  $0.3^\circ$  for electrons and gamma-rays in the  $10 \text{ GeV} - 1 \text{ TeV}$  energy range.

Prototypes of the CHD, IMC and TASC detectors were extensively tested at CERN SPS with beams of muons at 150 and 180 GeV energy, electrons with energies from 10 to 290 GeV, protons from 30 to 400 GeV, ion fragments at 13 and 30 GeV/nucleon. Results of the data analysis [5] demonstrate that the measured detector performances meet the design specifications.

## 2.2. CGBM instrument

The CGBM instrument [6] is dedicated to the observation of gamma-ray bursts (GRB) and other X-/gamma-ray transient phenomena, with a broad energy coverage from hard X-rays to soft gamma-rays, specifically in the range from 7 keV to 20 MeV; these data can be correlated with simultaneous gamma-ray observations of CALET-CAL instrument in the region from few GeV to several TeV.

The CGBM consists of two hard X-ray monitor (HXM) units and one soft gamma-ray monitor (SGM) unit, a support optical sensor given by the Advanced Sky Camera (ASC) and a GPS receiver (GPSR).

Each HXM unit contains a  $\text{LaBr}_3(\text{Ce})$  scintillator crystal read by a PMT (Hamamatsu Photonics R6232-05) and shaped as two superposed cylinders with diameter of 6.6 and 7.9 cm respectively and thickness 0.6 cm each. The  $\text{LaBr}_3(\text{Ce})$  scintillator is here used in space for the first time for celestial gamma-ray observations. The field of view is limited by a collimator within  $\approx 58^\circ$  from the vertical axis, to reduce possible contamination from cosmic X-ray background and bright X-ray astrophysical sources.

The SGM unit contains a BGO scintillator read a by PMT (Hamamatsu Photonics R6233-20) and shaped as a cylinder with 10 cm diameter and 7.6 cm thickness.

The energy resolution of HXM and SGM is  $\sim 3\%$  and  $\sim 15\%$ , respectively, at 662 keV.

### 3. CALET science

In the present section the main CALET science objectives are illustrated, as outlined below.

- Search for signatures of nearby astrophysical sources of cosmic rays (CR) in the multi-TeV cumulative  $e^-e^+$  energy spectrum; accurate and high-statistics spectral measurement in the 1 GeV - 20 TeV region, searching for dark matter signatures and fine spectral features. See Sect. 3.1.
- Search for dark matter signatures in the 10 GeV - 10 TeV gamma-ray spectrum; accurate spectral measurement of gamma-ray galactic/extragalactic background radiation and bright astrophysical sources. See Sect. 3.2.
- Study of CR acceleration and propagation mechanisms, with the measurement of nuclei spectra from H to the Fe region for energies from tens of GeV up to several TeV, with the measurement of the B/C flux ratio up to several TeV/nucleon and with the determination of abundances of ultra-heavy nuclei up to  $Z = 40$ . See Sect. 3.3.

Other important science items, not specifically treated here, are listed below.

- Detection and study of X-/gamma-ray transients in the energy region 7 keV - 20 MeV with the CGBM instrument.
- Study of solar modulation of the  $e^-e^+$  flux below  $\sim 10$  GeV.

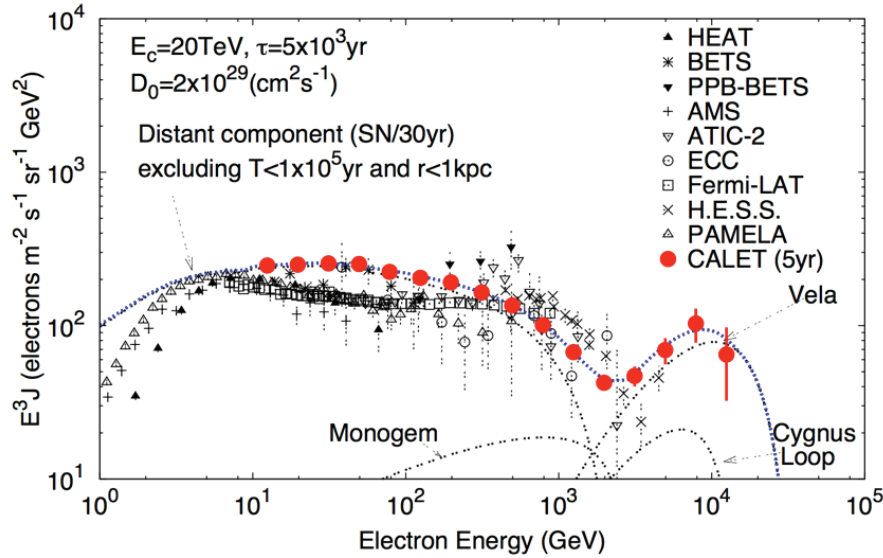
#### 3.1. Cosmic-ray electrons and positrons

Multi-TeV electrons originated in SuperNova Remnant (SNR) standard sources can be observed at Earth only if the SNR is younger than  $10^5$  years and within 1 kpc from the solar system, because of radiative synchrotron and inverse Compton energy losses, proportional to the squared energy, during propagation in the Galaxy [7]. Since the number of such nearby SNR's is very limited (Vela, Monogem, Cygnus Loop and few others), the electron energy spectrum around and above 1 TeV could exhibit spectral features and be characterized by a significant anisotropy<sup>35</sup> (order of 10%) in the arrival direction, related to the localization of the sources with respect to the galactic plane.

Among its contemporary experiments, CALET has unique capabilities for identifying such features in the multi-TeV region of cumulative  $e^-e^+$  flux, namely energy resolution, proton rejection power and angular resolution, together with a long exposure in space: for example,  $\sim 300$  events/yr from the Vela SNR component with  $E > 1$  TeV are expected to be collected and characterized after applying necessary data selection cuts, thus possibly giving a result as shown in figure 3. Besides, the CALET measurement will allow for tuning models of SNR sources, since the shape of CR electron flux in the multi-TeV range is critically affected (see e.g. [7]) by several model parameters which are still not precisely known, such as exponential cut-off energy of the accelerated spectrum, acceleration time interval, value of the diffusion coefficient.

Also in the sub-TeV energy region CALET accuracy and exposure will make it possible to significantly improve the knowledge of the detailed spectral shape and angular distribution of cumulative  $e^-e^+$  flux. This will help in identifying the additional unknown source, either an astrophysical object (e.g. a nearby pulsar) or annihilation/decay of dark matter particles, which has been suggested to explain recent measurements showing a clear change of slope, namely an

<sup>35</sup> The anisotropy  $\Delta$  is here defined by taking into account the maximum and minimum observed electron intensity with respect to the galactic longitude,  $I_{max}$  and  $I_{min}$ :  $\Delta = (I_{max} - I_{min}) / (I_{max} + I_{min})$ .



**Figure 3.** Expected cumulative  $e^-e^+$  energy spectrum measured with CALET after 5 years of observation, according to a possible SNR model as discussed in [7]: a distinctive signature of nearby SNR sources can be identified by CALET in the multi-TeV region. A selection of previous measurements is also reported.

$e^-e^+$  flux enhancement, in the range 200 GeV - 1 TeV, not expected for standard SNR sources (see e.g. [8] and references therein).<sup>36</sup>

### 3.2. Gamma-rays

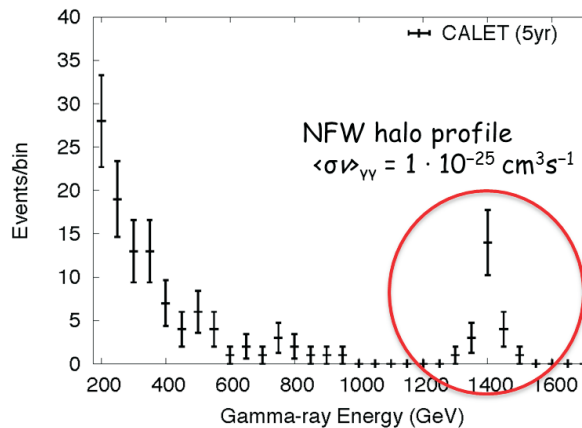
According to theories of annihilation or decay of dark-matter particles in the galactic halo, these phenomena should produce sharp gamma-ray lines in the sub-TeV to TeV energy region, superimposed on the diffuse spectrum. CALET [11] [12] will be capable of investigating such a distinctive signature, as shown e.g. in figure 4, thanks to the gamma-ray energy resolution of 3% above 100 GeV, which can be improved to 1% with a reduced (75%) on-axis effective area, obtained by selecting only events with the primary gamma-ray crossing all detector planes and at least 2 cm inside TASC layers (to assure complete lateral containment of the secondary shower).

CALET excellent energy resolution and good angular resolution (better than  $0.4^\circ$ , including pointing uncertainty) will allow for accurate measurements of diffuse gamma-ray emission and more than 100 bright sources at high latitude from the Fermi-LAT catalogue [13]. Given the on-axis effective area of  $\approx 600 \text{ cm}^2$  for energies above 10 GeV (reduced by  $\sim 50\%$  at 4 GeV) and field of view of  $\approx 45^\circ$  from the vertical direction, CALET is expected to detect  $\sim 25000$  ( $\sim 7000$ ) photons from the galactic (extra-galactic) background with  $E > 4 \text{ GeV}$  and  $\sim 300$  photons from the Vela pulsar with  $E > 5 \text{ GeV}$ .

### 3.3. Cosmic-ray protons and nuclei

It is still not clear to what extent the energy spectra of cosmic-ray nuclei in the 10 GeV - 1 PeV region are well described by a single power law  $E^{-\gamma}$  with  $\gamma \approx 2.7$ : in particular, the PAMELA collaboration [14] reported accurate measurements clearly indicating small but

<sup>36</sup> The presence of an additional source is also required to explain the now established rise of positron fraction in the 10 GeV - 500 GeV energy range (see e.g. [9], [10]).



**Figure 4.** Expected CALET 5-years measurement of a possible 1.4 TeV gamma-ray line from dark matter in the region of galactic centre, also including galactic diffuse background, according to [11].

significant deviations from single power law spectra for both H and He in the sub-TeV region, which still need to be compared with independent high-accuracy measurements.<sup>37</sup> The same measurements also show a clear difference of  $\approx 3\%$  between the spectral indexes of H and He: it is therefore reasonable to investigate similar differences for other nuclei species. Finally, it is still an open question whether there is a spectral cut-off (“knee”) below 1 PeV for the various nuclei species. These open points reflect in uncertainties in the understanding of the cosmic-ray shock acceleration mechanism taking place in SNR sources. More accurate measurements of the individual energy spectra of CR nuclei, especially approaching the PeV energy region, are therefore needed.

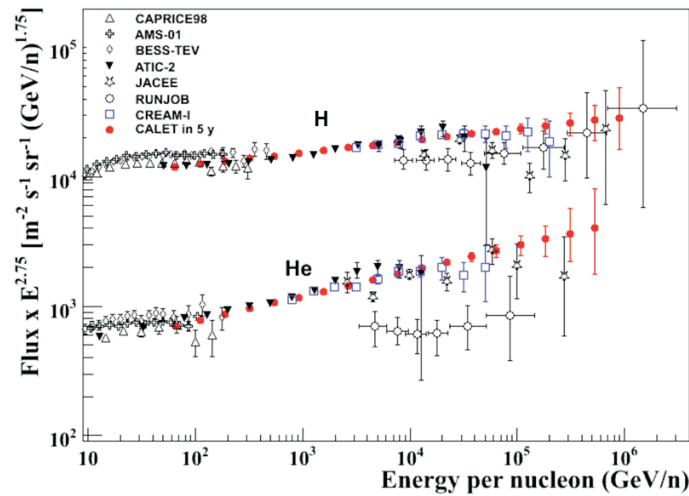
CALET will be able to identify CR nuclei with individual element resolution and measure their energies in the range from few tens of GeV to several hundreds of TeV. Its thickness ( $30 X_0$ ,  $1.5 \lambda_I$ ) allows for highly efficient nuclear interaction of the incoming nucleus and subsequent good confinement of the electromagnetic core of the secondary shower, thus achieving an energy resolution better than 35% for nuclei up to  $\sim 100$  TeV. In 5 years of data taking on the ISS, CALET is expected to measure the proton energy spectrum up to  $\sim 900$  TeV and the He spectrum up to  $\sim 400$  TeV/nucleon (see figure 5) and to determine the fluxes of the more abundant heavy nuclei with good statistical precision, up to  $\sim 20$  TeV/nucleon for C and O and  $\sim 10$  TeV/nucleon for Ne, Mg, Si and Fe.

Important information on the CR propagation in the galaxy is obtained from the secondary-to-primary flux ratio for CR elements, in particular the B/C ratio [17], which is known to follow a power law in energy  $E^{-\delta}$  for energies below  $\sim 100$  GeV/nucleon; an accurate measurement of  $\delta$  and the determination whether the B/C ratio deviates from a simple power law above  $\sim 100$  GeV/nucleon are crucial for discriminating between different models of CR propagation. CALET will provide new data to improve the accuracy of the present measurements above 100 GeV/nucleon and extend them above 1 TeV/nucleon: in 5 years, CALET can determine  $\delta$  with an absolute uncertainty of  $\pm 0.05$ .

Moreover [18], by exploiting the CHD particle identification capability, CALET will measure the abundances of ultra-heavy CR nuclei at few GeV/nucleon for Z up to 40, with an expected statistics in 5 years from 2 to 4 times larger than collected by the TIGER experiment.

<sup>37</sup> Preliminary measurements of H and He spectra have been published by AMS-02 collaboration [15] [16], without quantitative comparisons with PAMELA results.





**Figure 5.** Expected CALET measurement of the energy spectra of H and He after 5 years of observation, compared with a selection of previous direct measurements.

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